

Agricultural Water Conservation— A Global Perspective

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SUMMARY. Water for agriculture generally is adequate in humid regions, but water conservation often is needed in subhumid and semi-arid regions for good crop production, even with irrigation because of limited supplies. Increasingly, urban, industrial, environmental, and recreational users compete for agricultural water supplies. Although temporally and spatially variable, annual total supplies are relatively constant. The increasing competition, therefore, makes it imperative that agriculture does its share to conserve water to achieve greater production for an ever-increasing populace. In this report, we discuss basic principles of and some practices for achieving agricultural water conservation, both under dryland (rainfed) and irrigated conditions. [Article copies available for a fee from The Haworth Document Delivery Service: 1-800-342-9678. E-mail address: getinfo@haworthpressinc.com <Website: <http://www.haworthpressinc.com>>]

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INTRODUCTION

All plants depend on an adequate water supply for optimum growth and development. For terrestrial plants, water stored in soil from precipitation or

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irrigation sustains plants until the next precipitation or irrigation event. In humid regions, precipitation often is frequent enough so that plants seldom experience a water deficiency, and removal of excess water sometimes is required for successful crop production. As a result, water conservation for agricultural crops often receives little attention in humid regions. Short-term droughts, however, occur and water conservation can be beneficial for crop production, even in humid regions. Water conservation in humid regions may be especially beneficial on soils with low water holding capacity because 7 to 14 days without rain often causes severe plant water deficiencies and major crop yield reductions. We will give some examples for humid conditions, but will stress agricultural water conservation in subhumid and semiarid regions for dryland agriculture and semiarid and arid regions for irrigated agriculture.

Precipitation in subhumid and semiarid regions often is limited, with periods of various duration without precipitation occurring during the growing season of most crops. During such periods, the amount of plant available water in soil greatly affects growth and yield of dryland crops. For example, winter wheat (*Triticum aestivum* L.), grain sorghum (*Sorghum bicolor* [L.] Moench), and sunflower (*Helianthus annuus* L.) yields increased 7.2, 17.0, and 7.0 kg ha⁻¹, respectively, for each additional millimeter of plant-available water in Pullman soil (Torreptic Paleustoll) at planting time (Johnson, 1964; Jones and Hauser, 1975). Obviously, water conservation is highly important for dryland crop production in subhumid and semiarid regions, and water conservation has received much attention in such regions throughout the world.

Irrigation often is used for crop production where precipitation is limited, as in semiarid regions, and to extend production into arid regions. Sometimes, irrigation is used in subhumid and humid regions to supplement water from precipitation, especially during short-term droughts.

Successful irrigated agriculture depends on a reliable water supply, with the source being streams, reservoirs, or aquifers. Development of irrigated agriculture in a region usually is based on availability of adequate water. Subsequently, however, competition for water may develop to serve needs of urban, industrial, environmental, and recreational users, resulting in less water being available for irrigation. Also, the supply may be limited and is not being replenished in some aquifers. As a result, water removed for irrigation limits the amount available for future use, and declining water levels in aquifers will result in reduced pumping rates and greater energy requirements for pumping the water. The increasing competition for and declining supplies of water clearly show that less will be available for irrigation in the future and that irrigated agriculture must participate in water conservation efforts so that the needs of all users can be met. At present, agriculture is the largest consumer of water worldwide and is deemed largely inefficient in using the

water (Gleick, 1998). Postel (1992) estimated worldwide water use efficiency by agriculture at only 40%.

DRYLAND AGRICULTURE REGIONS

Dryland agriculture, also called dry farming (Cannell and Dregne, 1983), has been defined in various ways. According to the SSSA (1996), dryland farming is "crop production without irrigation (rainfed agriculture)." In the strictest sense, this definition would include farming in humid regions where precipitation may be excessive for successful crop production, at least for some crops. Although dryland agriculture is rainfed agriculture, others (Cannell and Dregne, 1983; Stewart, 1988) defined dryland agriculture (farming) as agriculture without irrigation where precipitation is low and erratic in amount and distribution, and generally less than potential evapotranspiration during a major part of the year. Use of special water-conserving practices usually is required for successful crop production under such conditions.

Dryland agriculture is practiced on all continents, except Antarctica, with about 600 million ha of land (~40% of the world's land surface) devoted to dryland agriculture (Brady, 1988). Dryland agriculture long has been a major provider of food and fiber products, and increased production of these products will be required under dryland conditions because of the ever-increasing world population. To achieve this, improved water conservation and use will be required because the total amount of water available annually is relatively constant.

IRRIGATED AGRICULTURE REGIONS

As of 1996, about 263 million ha of land were irrigated in the world, with irrigation being done in 166 countries (FAO, 1998). Most irrigated land was in India (57.0 million ha), the People's Republic of China (PRC) (49.9 million ha), and the United States of America (USA) (21.4 million ha), with the total for other countries being ~135 million ha. The irrigated area in the USA is relatively constant, but increases were shown for India, the PRC, and the total for other countries (FAO, 1998). Water available annually for irrigation and other users (competitors for water) is relatively constant. Therefore, water available for irrigation needs to be used more efficiently to achieve the increased production needed for the ever-increasing world population. As on dryland, improved water conservation on irrigated land will play a major role in assuring that adequate water will be available to produce the required agricultural products.

PRINCIPLES OF WATER CONSERVATION

Globally, individual tracts of land devoted to crops range from fractions of hectares for subsistence farmers to thousands of hectares for large private or commercial farms. Technologies involved may range from use of human or animal power to large tractors. Because of these size and technology differences, all water conservation practices are not equally applicable or adaptable for all conditions. The principles of water conservation, however, are applicable for all conditions, regardless of tract or equipment size.

Under all conditions, water conservation for agricultural crops depends first on water infiltration into soil and then its retention in that portion of the soil where it subsequently can be extracted by crop roots. Effective infiltration depends on conditions being favorable for adequate water flow into soil and on sufficiently low runoff rates that result in adequate time for water to enter soil. To retain water for later use by crops, evaporation, deep percolation, and use by weeds must be prevented or minimized. Water transport characteristics of a soil strongly influence water infiltration, evaporation, and deep percolation rates (van Bavel and Hanks, 1983).

Runoff water is of no direct value to a crop unless it is captured and used for irrigation or it enters a stream from which it can be used for irrigation at another site. To achieve maximum infiltration, runoff should be minimized or avoided. Runoff is avoided or minimized when the application rate (precipitation or irrigation) is at or below the soil's infiltration rate. Matching the water application rate to the infiltration rate is possible with many irrigation systems, but runoff often occurs with many surface irrigation methods and with mechanical move sprinkler systems. The application rate with precipitation, however, is not controllable and management practices are needed to reduce or prevent runoff, thus providing adequate time for infiltration. Soil surface and profile conditions, including the antecedent water content, influence the rate at which water infiltrates a soil.

Although runoff may be minimized or avoided, a soil often is not filled to capacity with water during one or even several precipitation events under dryland conditions in a semiarid region. Under such conditions, water harvesting may be used to supply additional water to a site or fallowing may be used to increase water storage for the next crop.

Water storage in a soil depends on such factors as its texture, organic matter content, profile depth, and horizon characteristics. Infiltrated water in excess of that needed to fill a soil to capacity is lost to deep percolation unless an impermeable layer is present. When deep percolation is hindered, runoff most likely will be greater and water-logging may occur.

Water retained in a soil is subject to evaporative loss from the surface. Loss is greatest during the first stage when the rate depends on the net effect of water transmission rate to the surface and aboveground conditions such as

wind speed, temperature, relative humidity, and radiant energy. Evaporation decreases rapidly during the second stage as the soil water supply decreases and when it depends on the rate of water movement to the surface. Third stage evaporation is low and controlled by adsorptive forces at the solid-liquid interface. The potential for decreasing soil water evaporation is greatest during the first two stages (Lemon, 1956). Methods for decreasing evaporation include decreasing turbulent water vapor transfer to the atmosphere (e.g., crop residues as a mulch), decreasing soil capillary continuity or capillary water flow to the surface (shallow tillage), and decreasing water-holding capacity of surface soil layers.

Water retained in a soil is subject to loss through transpiration by weeds. Weeds present before planting decrease the amount available for crop use. Those present during the growing season directly compete with crops for water in soil; also for light and space. In most cases, crop yields are reduced when weeds are not adequately controlled. Weed control is especially important for dryland crop production and for efficient use of irrigation water.

The above factors also affect water conservation under irrigated conditions. In addition, irrigation involves water conveyance from the supply point to the application site. Unless a closed system is used, water losses due to seepage, use by non-crop vegetation, and evaporation are possible. Seepage may be especially large from non-lined ditches.

Use of high-pressure sprinkler systems can result in large evaporative losses. Also, large deep percolation losses can occur when applied amounts exceed the soil's water storage capacity in the root zone. Deep percolation losses often occur with furrow or flood irrigation.

WATER CONSERVATION PRACTICES

Agricultural water conservation involves water storage in soil, except for that stored in reservoirs for irrigation. Numerous practices have been researched and are available for increasing soil water storage. Some are widely applicable; others only to highly specific conditions. Storage in reservoirs also generally is applicable only to highly specific conditions. We will emphasize the more widely applicable practices, but also will provide information regarding some other practices.

In addition to practices based on research, numerous indigenous and relatively simple practices are used by farmers in developing countries to obtain some water conservation benefits (Critchley et al., 1994; Gallacher, 1990). Evaluation and improvement of these practices with the farmers' participation could lead to improved water conservation in countries where more elaborate conservation practices would not be adaptable or acceptable.

Relationships among those factors important for improving water storage

in soil, namely, increasing infiltration (reducing runoff), reducing evaporation, eliminating or reducing water use by weeds, and eliminating or reducing deep percolation are highly complex. In many irrigation situations, deep percolation for salinity control and management is required and desired for sustainable crop production.

Infiltration and Runoff

Although runoff and infiltration are closely related (water lost as runoff cannot infiltrate) and reducing runoff is essential for increasing infiltration, all water retained on land does not necessarily infiltrate a soil. Rather, some water retained in surface depressions evaporates before infiltration occurs, especially when a surface seal or another restrictive layer is present. Also, water retained in surface soil often evaporates before it can be used by plants because it does not move deeply enough to add to the soil water supply. In some instances, infiltrated water may move laterally due to an impeding horizon and enter a stream, thereby contributing to runoff.

A soil must be receptive to applied water and sufficient time must be available for satisfactory infiltration to occur. Development of a soil surface seal (or crust) is a major deterrent to infiltration. When raindrops strike bare soil, their energy may disperse soil aggregates, thus resulting in seal development and runoff. In contrast, surface residues, as those resulting from use of conservation tillage, dissipate raindrop energy, thus preventing or reducing aggregate dispersion and seal development, and resulting in greater infiltration. Surface residues also retard the rate of water flow across the surface, thus providing more time for infiltration.

Numerous studies involving no-tillage, a type of conservation tillage, have shown the value of crop residues retained on the surface for increasing infiltration and, therefore, the potential for greater soil water storage (e.g., Cogle et al., 1996; Gilley et al., 1986; Harrold and Edwards, 1972; O'Leary and Connor, 1997; Opoku and Vyn, 1997). In general, runoff increases with increases in surface slope, especially on bare soils. With no-tillage, however, surface slope has less effect on runoff (Table 1). Although water contents were not given, reducing runoff provided the opportunity to replenish the soil water supply, which is the goal for water conservation efforts under all conditions. Besides reducing runoff, use of no-tillage also greatly reduced erosion.

Use of tillage may reduce runoff (increase infiltration) when residue amounts are low because of low production (as by dryland crops), use for other purposes, or incorporation by previous tillage. Under such conditions, tillage can disrupt a surface seal (crust), create contour ridges, and increase surface roughness and plow-layer pore space, thus retaining more water on the surface and providing more time for infiltration (Hien et al., 1997; Muchi-

TABLE 1. Tillage effects on runoff and sediment yield from watersheds planted to corn at Coshocton, Ohio, USA, during a severe storm in July 1969.^a

Tillage	Slope (%)	Rainfall (mm)	Runoff (mm)	Sediment yield (Mg ha ⁻¹)
Plowed, clean tilled, sloping rows	6.6	140	112	50.7
Plowed, clean tilled, contour rows	5.8	140	58	7.2
No-tillage, contour rows	20.7	129	64	0.07

^a Adapted from Harold and Edwards (1972).

ri and Gichuki, 1983; Rawitz et al., 1983; Stroosnijder and Hoogmoed, 1984; Willcocks, 1984). Greater infiltration and, hence, greater water storage also can be achieved by disrupting slowly permeable or compact layers in the profile (Eck and Taylor, 1969; McConkey et al., 1997; Schneider and Mathers, 1970) or loosening soils subject to freezing (Pikul et al., 1996). These practices increase the depth at which water is stored, thus enlarging the zone in which roots proliferate.

Other practices for increasing infiltration and water storage include graded furrowing (Krantz et al., 1978; Pathak et al., 1985; Richardson, 1973), terracing (Beach and Dunning, 1995; Gallacher, 1990; Jones, 1981), furrow diking (tied ridging) (Gallacher, 1990; Jones and Clark, 1987; Vogel et al., 1994), strip cropping and growing vegetative barriers (Alegre and Rao, 1996; Gallacher, 1990; Sharma et al., 1997), and using LEPA (low energy precision application) irrigation. Water application efficiencies were > 95% with LEPA irrigation (Howell et al., 1995; Lyle and Bordovsky, 1983; Schneider and Howell, 1990). With LEPA irrigation, water often is applied to alternate diked furrows to temporarily detain water on the surface. Diked furrows can be used with most sprinkler methods to temporarily impound "excess" water to provide more time for infiltration.

Snow provides much of the water for crops in the northern U.S. Great Plains, Canadian Prairie Provinces, northern Europe, and northern Asia. A special case involving crop residues or vegetative barriers is their use to trap snow, thus achieving greater and more uniform soil water storage when the snow melts (Black and Aase, 1988; Campbell et al., 1992; Cutforth and McConkey, 1997; Steppuhn and Waddington, 1996). Under some conditions, snow is "plowed" into ridges to create barriers for greater trapping of snow during subsequent storms (De Jong and Steppuhn, 1983). Soil water storage from snow is highly variable, but up to 50 mm more storage occurred with than without residues or barriers in place. Vegetative factors influencing snow trapping include stubble height, barrier spacing, and barrier orientation relative to wind direction. Greater soil water contents resulting from trapped

snow permitted more intensive cropping and resulted in greater crop yields. The barriers also provided microclimate benefits for the next crop. Under some conditions, the greater soil water contents contributed to development of saline seeps (Black and Siddoway, 1976), thus reducing crop yields. Careful matching of crops to the available water supply helps avoid the saline seep problem (Brown et al., 1982).

The surface of some soils is highly unstable, and runoff is common when the soil is not protected by residues or other runoff control practices. Some materials applied directly to soils or with irrigation water have resulted in major increases in infiltration as compared to that where the materials were not applied. Runoff was reduced sixfold as compared with that from untreated soil when phosphogypsum (PG) was applied at 10 Mg ha^{-1} to a ridged sandy soil in Israel under field conditions (Agassi et al., 1989). When PG was applied to a clay loam at 3.0 Mg ha^{-1} , runoff was less than from bare soil, but still greater than where wheat straw was applied at 2.2 Mg ha^{-1} (Benyamini and Unger, 1984). Anionic polymers [polyacrylamide (PAM) or starch copolymer solutions] injected into water used for furrow irrigating a silt loam in Idaho (USA) reduced soil loss in runoff 70% when applied at 0.7 kg ha^{-1} per irrigation and 97% when applied at 10 g m^{-3} of water. The treatments also increased net infiltration and lateral infiltration, probably because of less surface sealing and sediment movement (Lentz et al., 1992; Trout et al., 1995).

Evaporation

Precipitation storage as soil water during the interval between crops in a semiarid region such as the U.S. Great Plains usually is $< 50\%$, with amounts much below that occurring in many cases (Jones and Popham, 1997; Unger, 1978, 1994). While runoff accounts for some water loss, Bertrand (1966) indicated $\sim 60\%$ of average annual precipitation may be lost directly from soil by evaporation. Evaporative losses can be especially large when most precipitation occurs in relatively small storms. For example, 1522 storms occurred at Bushland, Texas (USA), in the southern Great Plains from 1960 through 1979. Precipitation occurred at $\sim 100 \text{ mm hour}^{-1}$ for up to 10 minutes in some storms, but total precipitation was $> 50 \text{ mm}$ for only 11 storms and $> 25 \text{ mm}$ for only 73 storms (unpublished data, Conservation and Production Research Laboratory, Bushland, TX). Small storms result in limited soil wetting and significant evaporative losses. Consequently, water storage efficiencies at Bushland generally are low because most storms occur in summer when the evaporation potential is greatest (Jones and Popham, 1997; Unger, 1978, 1994). Evaporation from fully wetted soils, however, also results in major water losses (Plauborg, 1995).

Soil water evaporation is a highly complex process because it involves

water movement as liquid or vapor in response to soil water potentials, soil temperature gradients, and atmospheric conditions. In addition, deep percolation may occur while evaporation occurs from the surface. As a result, determining evaporation under field conditions is difficult because of the interacting effects of water infiltration, distribution in soil, deep percolation, and subsequent evaporation.

Effects of many surface mulch treatments on soil water evaporation have been studied (Unger, 1995), with crop residues used as the mulch in many cases. Residue characteristics affecting evaporation are orientation (flat, matted, or standing), which affects layer porosity and thickness; layer uniformity; rainfall interception; reflectivity, which affects surface radiant energy balance; and aerodynamic roughness resulting from the residues (Van Doren and Allmaras, 1978).

Although difficult to measure, results of some field studies clearly showed that retention of crop residues on the soil surface reduced evaporation. During 5 weeks without precipitation, water loss was 23 mm from bare soil, but only 20 mm with flat, 19 mm with 0.75 flat-0.25 standing, and 15 mm with 0.50 flat-0.50 standing wheat residue on the surface (Smika, 1983). Standing residue was 0.46 m tall and the amount was 4600 kg ha^{-1} in all cases. Greater wind speed was needed to initiate water loss as the amount of standing residue increased and the water loss rate decreased with increasing amounts of standing straw at a given wind speed. Residue orientation also affected average surface soil temperature (47.8, 41.7, 39.6, and 32.2°C for the respective conditions), which, in turn, affected evaporation through its effect on vapor pressure of soil water (Smika, 1983). Nielsen et al. (1997) showed that potential evaporation decreased as residue height increased, with the height effect being especially important when stem density was $< 215 \text{ m}^{-2}$. The height effect decreased with increasing stem densities.

One day after a 13.5 mm rain, soil water contents were similar to a 15-cm depth where conventional-, minimum-, and no-tillage treatments were imposed after winter wheat harvest at Akron, Colorado (USA). Surface residue amounts were 1200, 2200, and 2700 kg ha^{-1} with the respective treatments. After 34 days without more rain, soil had dried to a $< 0.1 \text{ m}^3 \text{ m}^{-3}$ water content to a depth of 12 cm with conventional tillage and 9 cm with minimum tillage. Blade tillage had been performed to those depths 8 days before the rain. With no-tillage, soil had dried to that water content only to a 5-cm depth. Some loss occurred at greater depths with each treatment, but water content was greatest with no-tillage for which the surface residue amount was greatest (Smika, 1976).

Evaporation reduction in the above studies involving crop residues resulted primarily from reduced turbulent transfer of water vapor to the atmosphere. Another means of reducing evaporation is to reduce capillary water

flow to the surface. Therefore, there long has been an interest in using dust mulching (also called soil mulching) to reduce soil water evaporation. Dust mulching is essentially a clean-tillage (residue-free) system that involves producing a loose, fine granular or powdery soil layer at the surface by shallow tillage or cultivation. Dust mulching, in general, is effective for reducing evaporation of water already present in soil (Abdullah et al., 1985; Jalota, 1993; Jalota and Prihar, 1990; Papendick, 1987; Singh et al., 1997). Therefore, it is applicable mainly to regions where a distinct wet (rainy) season is followed by a distinct dry season. It usually is ineffective where precipitation mainly occurs when the potential for evaporation is greatest, as in summer in the U.S. Great Plains, because much of the water evaporates before tillage can be performed (Jacks et al., 1955). Dust mulching also is not suitable for such regions because the frequent tillage needed to maintain the mulch results in the soil being highly susceptible to erosion. Another reason for poor results with dust mulching in a summer precipitation region is that tillage brings moist soil to the surface, which increased evaporation and, in turn, resulted in less water storage where stubble mulch rather than no-tillage was used (Jones and Popham, 1997).

Water Retention

Water retention is influenced mainly by a soil's texture, structure (aggregation and porosity), depth, and organic matter content. A soil's texture is an inherent trait resulting from the conditions under which the soil developed. Sandy soils generally have lower water holding capacities than finer-textured soils (higher silt and clay contents). Deep plowing to mix profile layers or to bring finer materials to the surface increased the water holding capacity of soils initially having a surface horizon with a high sand content (Harper and Brensing, 1950; Miller and Aarstad, 1972). Besides increasing water retention in a given volume of soil, deep plowing and profile mixing also increase the depth to which plant roots can proliferate and extract water (Eck and Taylor, 1969; McConkey et al., 1997; Schneider and Mathers, 1970). These operations require special equipment; are energy-intensive, costly, and time consuming; and are not widely used, except where major benefits can be achieved. Chiseling is a less intensive operation often used to disrupt restrictive zones at relatively shallow depths, especially in irrigated soils.

Organic matter influences soil water retention through its direct affinity for water and its effect on aggregation, both of which increase with increases in organic matter content. Returning all or most crop residues to a soil helps maintain or, under some conditions, increase the soil's organic matter content. Maintaining or increasing a soil's organic matter content under dryland conditions in a semiarid region such as the southern U.S. Great Plains, however, is difficult because residue production generally is low. Rather, soil

organic matter contents generally decreased with continued cropping with clean or stubble mulch (sweep) tillage and tended to be maintained, but not increased, under no-tillage conditions (Potter, 1998; Unger, 1997).

Whereas increasing a soil's organic matter content to increase water retention is difficult, there long has been an interest in adding organic substances to soils to improve water conservation (Unger and Stewart, 1983). Applying organic substances to soil resulted in less runoff (Weakly, 1960) and evaporation (Olsen et al., 1964), but the potential was limited under field conditions because the substances had limited stability in soil and little effect on crop yields.

Some recent reports indicated that adding coal-derived humic substances (Piccolo et al., 1996) and synthetic polymers (Choudhary et al., 1995) to soils significantly increased water retention. In a laboratory study, adding humic substances to soil at a 0.05 g kg^{-1} rate increased the available water content by up to 5.2% as compared with untreated soil, with no further increases when applied at rates up to 1.0 g kg^{-1} . The 0.05 and 0.10 g kg^{-1} rates of application resulted in 40 and 120% increases in soil aggregate stability, respectively, which contributed to the greater water retention. Further studies were needed to evaluate the potential of the substances under field conditions (Piccolo et al., 1996). Also under laboratory conditions, Choudhary et al. (1995) added synthetic polymers to two soils at rates of 0.2, 0.4, and 0.6% on a dry weight basis. Increases in amount of polymer applied resulted in greater water conservation by increasing the soils' water holding capacity and by decreasing evaporation as compared with that of untreated soil. The water retention benefits achieved were attributed to the hydrophilic groups in molecules of the applied polymers (Piccolo et al., 1996).

Weed Control

Where the need for water conservation for crop production is critical, it is imperative that water use by weeds be avoided or minimized. This is especially the case under dryland conditions in semiarid regions because water use by weeds reduces the amount available for the crop, thus reducing crop yields. Avoiding competition between weeds and crops for water is important not only during a crop's growing season, but also before planting when storing as much water as possible for the crop to be grown is the goal. Weeds also compete with crops for light, nutrients, and space; therefore, their control is important under all cropping conditions.

Land under dryland conditions generally must be kept free of weeds to obtain maximum soil water storage at planting time. Until herbicides became available, a major reason for tillage was to control weeds. Now, tillage and/or herbicides can be used for weed control. Under some conditions, hand weed-

ing may be practiced. Also, use of crop rotations reduces the severity of some weed problems (Wiese, 1983).

Regardless of the method, timely control is important because uncontrolled weeds may use about 5 mm of water per day from a soil (Wicks and Smika, 1973). When using tillage, it usually can be delayed until weeds use more water than that lost by evaporation, thus avoiding frequent tillage operations and, thereby, resulting in production cost and energy savings (Lavake and Wiese, 1979). Another consideration is that each tillage operation exposes moist soil to the atmosphere, thus also contributing to evaporative soil water losses. Good and Smika (1978), for example, showed that each tillage operation resulted in losing 5 to 8 mm of water from the exposed moist soil. An advantage of using tillage for weed control is that water loss due to transpiration stops almost immediately, thus preventing continued water loss that may occur when herbicides are used. Several tillage operations may be needed to maintain weed control and to obtain optimum water conservation and crop yields (Pressland and Batianoff, 1976).

Small-scale farmers in many countries such as those in sub-Saharan Africa commonly control weeds by hand (Twomlow et al., 1997). As with tillage, repeated weeding usually is needed to achieve optimum crop production. In Zimbabwe, for example, weeding at 2, 4, and 6 weeks after corn (*Zea mays* L.) emergence resulted in greater water use efficiency and grain yield than a single weeding at 2 weeks. The unweeded control treatment resulted in the driest soil and lowest yields.

Herbicides can be applied to prevent weed seed germination or to control existing weeds. Preventing germination would be ideal for preventing soil water loss due to transpiration by weeds. However, use of such herbicides may not prevent germination of all weed seeds in a given crop because some weeds are not controlled by the herbicide. Use of "safener-treated" crop seed (seed treated to prevent action of a herbicide) has extended the use of some herbicides to prevent weed seed germination (Jones and Popham, 1997).

For established weeds, timely control is highly important for minimizing their competition with crops for water. In general, small weeds are easier to control than large weeds (Wiese et al., 1966). Weeds not killed immediately continue to use soil water. Weed control with herbicides often becomes especially difficult when plants are stressed for water. Development of herbicide-tolerant crops through genetic engineering has greatly expanded the opportunity for using highly-effective, quick-acting herbicides to control problem weeds in some crops.

Cover crops maintain a cover on the soil surface, thereby "preventing soil erosion, improving water infiltration, maintaining and increasing organic carbon levels, and possibly improving soil productivity" (Tyler, 1998). Although generally not considered to be weeds, cover crops and weeds affect

the water supply for subsequent crops similarly. Use of cover crops generally had little effect on the soil water supply for the next crop in humid and subhumid regions because of generally adequate precipitation. However, where the goal is to increase soil water storage for the next crop (e.g., under dryland conditions in the semiarid portion of the U.S. southern Great Plains), growing cover crops usually is not recommended (Unger and Vigil, 1998) because their use generally reduced the soil water content at planting time and yield of the next crop.

Multiple-Factor Water Conservation Practices

For studies under field conditions, factors resulting in soil water content differences usually are not clearly differentiated. Rather, at any given time, prevailing water contents reflect the combined effects of water infiltration, runoff, evaporation, retention, and weed control, which were discussed separately in foregoing sections. The literature pertaining to soil water conservation is vast. In this section, some selected examples of the combined effects of the different factors are given and discussed.

Fallowing

Fallowing is the practice of allowing cropland to remain idle during all or part of the growing season when a crop normally would be grown. Objectives often are to control weeds, accumulate soil water, and/or accumulate plant nutrients. Fallowing often is used under dryland conditions in semiarid regions, primarily to provide more time to increase soil water storage for the next crop, thus increasing the yield potential and reducing the probability of a crop failure. Use of fallowing generally increases the soil water content at planting of the next crop, but precipitation storage as soil water (known as fallow efficiency or water storage efficiency) often is low. This is especially the case where long fallow periods are used such as those involving winter and spring wheat in the Canadian Prairies and U.S. Great Plains.

The winter wheat-fallow and spring wheat-fallow systems result in one crop in 2 years; they involve 14 to 17 and ~21 months of fallow between crops, respectively. Use of these systems improved and stabilized crop production in the Great Plains starting early in the 20th century, but water storage efficiencies generally were < 20%. Through the introduction of improved equipment, crop residue management techniques, and weed control practices (including the use of herbicides), water storage efficiencies of ~50% have been achieved under some conditions (Smika, 1986). Water storage efficiencies and crop yields resulting from use of improved practices in the U.S. central Great Plains are illustrated in Table 2.

TABLE 2. Improvements in fallow systems with respect to soil water storage and wheat grain yields at Akron, Colorado, USA.^a

Year	Tillage during fallow	Fallow water storage		Wheat yield (Mg ha ⁻¹)
		(mm)	(% of precip.) ^b	
1916-30	Maximum; plow, harrow (dust mulch)	102	19	1.07
1931-45	Conventional; shallow disk, rod weeder	118	24	1.16
1946-60	Improved conventional; begin stubble mulch in 1957	137	27	1.73
1961-75	Stubble mulch; begin minimum with herbicides in 1969	157	33	2.16
1976-90	Projected estimate; minimum, begin no-tillage in 1983	183	40	2.69

^a Adapted from Greb (1979).

^b Based on percentage of soil water storage of precipitation received from wheat harvest in July to end of fallow in September (14-month period).

Storage efficiencies are highly variable among years and generally are greater in northern regions (US northern Great Plains and Canadian Prairies) than in southern regions (US southern and central Great Plains). In the northern Great Plains, average storage efficiency was 28%, but ranged from 16 to 44% from 1957 to 1970 (Black and Bauer, 1986). Water storage efficiencies resulting from use of various cropping systems and tillage methods in the southern Great Plains are given in Table 3. With improved storage efficiencies, more intensive cropping is possible and some well-adapted systems have been developed.

Crop Selection and Cropping Systems

Crops (also crop varieties or cultivars) vary in length of growing season and usually have peak growth periods at different times of the year. Therefore, for optimum production, major water requirement periods of selected crops should closely match periods of greatest potential water availability (stored soil water or precipitation). For example, winter wheat in the southern and central Great Plains is maintained during the fall and winter months mainly by water contained in soil at planting time. Although some soil water may remain for the peak demand period in spring (April till June), best yields are obtained when favorable precipitation occurs during that period, which includes the period of greatest precipitation probability in the region. Therefore, winter wheat is well adapted for that region.

TABLE 3. Cropping system and tillage method effects on average water storage efficiency during fallow before grain sorghum and winter wheat crops at Bushland, Texas, USA, 1984-1993.^a

Cropping system and tillage method	Storage efficiency (%) ^b
Fallow before sorghum	
Continuous sorghum-stubble mulch	27.3 (4.1)
Continuous sorghum-no-tillage	32.0 (4.5)
Wheat-sorghum-fallow-stubble mulch	16.5 (2.1)
Wheat-sorghum-fallow-no-tillage	21.0 (2.3)
Fallow before wheat	
Continuous wheat-stubble mulch	13.9 (4.0)
Continuous wheat-no-tillage	19.8 (4.1)
Wheat-fallow-stubble mulch	10.6 (1.8)
Wheat-fallow-no-tillage	11.1 (2.1)
Wheat-sorghum-fallow-stubble mulch	17.0 (2.0)
Wheat-sorghum-fallow-no-tillage	16.8 (2.0)

^a Adapted from Jones and Popham (1997).

^b Storage efficiency = soil water storage during fallow as a percentage of fallow-season precipitation. Values in parentheses are the standard error of the mean.

Summer crops also are well adapted for the southern and central Great Plains because their growing season roughly corresponds to the time when rain is most likely to occur. Summer crops, however, differ in growing season length and, therefore, vary in adaptability. For example, sugar beet (*Beta vulgaris* L.) has a long growing season, requires a large amount of water, and generally yields poorly on dryland. Grain sorghum has a shorter growing season, requires less water than beet, and generally yields well unless water is limited during the critical grain filling period. Grain sorghum yield also is strongly influenced by the soil water content at planting (Jones and Hauser, 1975; Unger and Baumhardt, 1999). Short season crops such as millet (*Pennisetum* spp.) and some hay crops require less water and, therefore, generally produce more with a given amount of water than wheat or sorghum (Greb, 1983).

For greatest water storage after crop harvest, a crop should use most plant-available water by the time it is harvested, thus providing a soil receptive to storing water. Of course, water remaining in soil at harvest may also be available for the next crop, especially when shallow- and deep-rooted crops are grown in rotation.

The foregoing pertained mainly to crops grown annually on the same tract of land (continuous or annual cropping). The crops mentioned, along with others [corn, sunflower (*Helianthus annuus* L.), etc.], generally are well adapted for use also in crop rotations. Use of crop rotations may provide more time for soil water storage (e.g., winter wheat-grain sorghum-fallow rotation; two crops in 3 years with 10 to 11 months of fallow between crops); greater extraction of soil water (use of shallow- and deep-rooted crops, mentioned above); and better weed, insect, and disease control (use of different pesticides, tillage methods, and other management practices). All of these have water conservation ramifications, and successful dryland crop production frequently involves the use of crop rotations.

The introduction of improved equipment, crop residue management techniques, and weed control practices has resulted in greater water storage efficiencies, thus providing an opportunity for more intensive cropping. Because water storage efficiency was generally low with the wheat-fallow system, it has been replaced by more intensive cropping systems under dryland conditions in many cases. Well-adapted systems include winter wheat-fallow-grain sorghum-fallow (two crops in 3 years) in the southern and central Great Plains (Jones and Popham, 1997; Norwood, 1992; Unger, 1994) and winter wheat-corn (or grain sorghum)-millet-fallow (three crops in 4 years) in the central Great Plains (Wood et al., 1991). In the northern Great Plains, systems of spring wheat-winter wheat-fallow (two crops in 3 years); safflower (*Carthamus tinctorius*)-barley (*Hordeum vulgare* L.)-winter wheat; spring wheat-corn-peas (*Pisum sativum*); spring wheat-winter wheat-sunflower; and spring wheat in rotation with soybean (*Glycine max* L.), peas, safflower, sunflower, buckwheat (*Fagopyrum esculentum* Moench), or canola (*Brassica* spp.) are being used (Black, 1986; Black and Tanaka, 1996; Unger and Vigil, 1998). Under some conditions, use of improved management practices for continuous (annual) cropping systems has increased soil water storage, thus resulting in greater total yields than for crops grown in rotation systems (Campbell et al., 1998; Jones and Popham, 1997). More intensive cropping was reported also by Amir and Sinclair (1996), Carroll et al. (1997), and Sandal and Acharya (1997).

Mulching

Although many materials are available, crop residues usually are used as the mulch under field conditions. In essence, conservation tillage (including no-tillage) is a mulch tillage system. By definition, conservation tillage is any system that results in at least 30% residue cover on the soil surface after crop planting to control water erosion. For wind erosion control, residues equivalent to 1000 kg ha⁻¹ of small grain residues should be present. Besides controlling erosion, crop residues retained on the soil surface also provide

TABLE 4. Straw mulch effects on average soil water storage during fallow, storage efficiency, dryland grain sorghum yield, and water use efficiency for grain production, Bushland, Texas, USA, 1973-1976.^a

Mulch rate (Mg ha ⁻¹)	Water storage (mm) ^b	Storage eff. (%) ^b	Grain yield (kg ha ⁻¹)	Water use eff. (kg m ⁻³) ^c
0	72 c ^d	22.6 c	1.78 c	0.56
1	99 b	31.1 b	2.41 b	0.73
2	100 b	31.4 b	2.60 b	0.74
4	116 b	35.6 b	2.98 b	0.84
8	139 a	43.7 a	3.68 a	1.01
12	147 a	46.2 a	3.99 a	1.15

^a Adapted from Unger (1978).

^b Water storage determined to 1.8-m depth; precipitation during fallow averaged 318 mm; fallow was 10 to 11 months.

^c Water use efficiency based on grain produced, growing season rainfall, and soil water content changes during growing season.

^d Column values followed by the same letter are not significantly different at the 0.05 level (Duncan's multiple range test).

water conservation benefits (Table 4). Greatest water conservation resulted from the high residue treatments, but dryland crops usually produce < 4 Mg ha⁻¹ of residue. Therefore, water storage usually is lower, but still greater than where some or most crop residues are incorporated by tillage, as reported extensively in the literature. Conservation tillage, especially no-tillage, is an effective water conservation practice, even under dryland conditions.

Vertical or slot mulching is a specialized type of mulching that involves opening a slot in soil with a suitable implement (e.g., a chisel) and filling the slot with crop residues or other materials (Ramig et al., 1983; Raper et al., 1998). The mulch-filled slot provides for rapid infiltration, provided the opening to the surface is not closed by subsequent tillage. On a soil subject to freezing in the state of Washington (USA), runoff from land planted to wheat was 10 mm with slot mulching compared with 114 mm with no-tillage, resulting in the potential to increase wheat yields by 1300 to 2000 kg ha⁻¹ (Ramig et al., 1983).

Water Harvesting

Ancient stone mounds and water conduits in some countries indicate water harvesting has long been used to capture or divert storm runoff for application to land where crops are grown. The water may be applied directly to cropland or retained in reservoirs for irrigating a crop at a later time. The

runoff may be from natural land surfaces or from surfaces treated to enhance runoff (Abu-Awwad and Shatanawi, 1997; Frasier and Myers, 1983; Greb, 1979; Laing, 1981; Lavee et al., 1997).

Direct application of harvested water to crops generally is practiced where precipitation is limited, as in semiarid to arid regions. The goal is to capture water falling on a given area and supplement it with runoff from a contributing area. The receiving area should be capable of retaining the initial and runoff water without adversely influencing the crop being grown. Systems used for direct application of the harvested water include level pans that receive water diverted from natural waterways (Greb, 1979); conservation bench terraces for which runoff from the natural upslope area is captured on the leveled downslope area between terraces (Zingg and Hauser, 1959); level, intermittent, fish scale, and discontinuous parallel terraces for which runoff from part of the land is captured by the terraces (Unger, 1996); and various types of microbasins. Land preparation for receiving harvested water directly generally involves limited modification of the soil surface.

Where runoff is stored for later crop use, the reservoir's capacity should be adequate to hold the amount needed for irrigation, with normal frequency of runoff events and reservoir "leakage" (percolation and evaporation) influencing the capacity. Water storage in a reservoir is most frequently used in subhumid and humid regions or where distinct rainy seasons are followed by distinct dry seasons, as in parts of India (Krantz et al., 1978) and other countries.

Water conserved and crop yields resulting from water harvesting are highly variable because runoff amount and timing relative to crop requirements are highly variable (Greb, 1979; Kaushik and Gautam, 1994), especially where runoff is directly used on the land. More reliable crop yields are possible when adequate runoff is stored and used as needed for irrigation.

Crop Termination Time

When grain crops such as corn, wheat, and grain sorghum reach physiological maturity, subsequent water use does not increase their yield. Water use after physiological maturity, however, could influence a crop's harvested yield by delaying lodging until harvest is possible. Because yield potential is not increased, terminating the crop at physiological maturity would halt soil water extraction and, thereby, conserve some water for the next crop. An alternative would be to terminate plant growth immediately after harvest for crops such as grain sorghum and cotton (*Gossypium hirsutum* L.) that have an indeterminate growing season where their growth is not terminated by cold weather. Of course, second or ratoon crops are possible under some conditions [e.g., grain sorghum, sugarcane (*Saccharum* sp.), and rice (*Oryza sativa*)]. The ratoon crop most likely would require less water than the first crop because limited additional plant development would be required.

Irrigation Water Delivery Systems and Irrigation Methods

Ideally, all irrigation water would be delivered to crops without loss and at the precise time to provide the greatest benefit. Irrigation delivery may involve transporting water from a sole supply like a dedicated reservoir or a single well where one person (or company) may have complete control. Most often, however, the water is from off-site sources and its transport in conveyances varies from pipelines under various pressures (low for gravity surface flow to high for sprinklers) or canals with small head differences above the field surface itself. Sources may be streams, reservoirs, or aquifers. Irrigation water supplies often involve many institutions and legal and/or social organizations that can have a myriad of rules, regulations, and/or laws as well as varying purposes for operation.

Goals for irrigation water conservation are to achieve the greatest economic benefits (perhaps even social or political benefits) from the water applied and to provide for sustainable agriculture. The water often is a shared resource and some application and operational losses (i.e., canal spillage, return flow into streams, surface runoff, required leaching for salinity control, etc.) are regained and subsequently used by downstream irrigators. Therefore, it is difficult to characterize irrigation water conservation without defining it on a hydrologic and/or irrigation district scale (Burt et al., 1997). Even if defined precisely, it is challenging to characterize all possible components and pathways for water losses and water movements. For this report, we discuss irrigation water conservation from a field-level perspective, but we recognize the critical importance of the off-farm delivery network for achieving any water conservation goal.

Each water conservation principle discussed for dryland agriculture is equally important for irrigated agriculture. The goal of irrigation is to use the greatest fraction of the applied water to meet the crop's transpiration need. Losses to runoff (from rain or irrigation), evaporation (from plant and soil surfaces), and excess deep percolation (except that needed to maintain root zone salinity at a safe level) remain the central components of inefficient irrigation and offer the pathways for achieving enhanced irrigation water conservation. Spatial distribution of rainfall cannot be controlled, but spatial uniformity of irrigation applications remain important for successful irrigation water conservation. Irrigation spatial and temporal distribution are controlled exclusively by management and the method used. "Irrigation management consists of determining when to irrigate, the amount to apply at each irrigation and during each stage of plant growth, and the operation and maintenance of the irrigation system" (Hoffman et al., 1990; p. 9). Irrigation timing depends largely on the crop and soil water status, but the delivery schedule may be controlled by the water supplier, which can impede a producer's water conservation goals. The desired application amount also re-

mains intertwined with the delivery schedule, crop need, and application technology. Likewise, operation and maintenance needs are directly impacted by the application method and technologies. In some cases, the crop grown may dictate using a certain application technology (i.e., to keep water off the fruit or plant).

Irrigation Technology for Conserving Water

In most countries, some form of surface irrigation technology is still used mainly because capital to acquire newer technology may be limited, skills for using the newer technology may be unavailable, or institutions desire to use manual labor (to maintain and support an agrarian populous). In the Jiftlik Valley in Jordan, switching 'from flood to drip-trickle irrigation (higher technology) resulted in increasing the irrigated area 10-fold while using the same amount of water. In addition, use of the drip-trickle method allowed more intensive cropping, which resulted in greater labor use, allowed repayment of loans for equipment in 3 to 4 years, increased income 13- to 15-fold, and increased off-farm benefits (commercial inputs) eight-fold (Keen, 1991). Improving irrigation application efficiency on the farm may not improve it on the larger-scale hydrologic or district level unless that change results in smaller non-recoverable losses (i.e., to non-reusable saline waters, to the vadose zone beneath the crop root zone that will not move to recoverable groundwater, etc.).

Surface irrigation often is termed "inefficient" because of large deep percolation and/or runoff losses that result from relying on soil to transport and distribute the water. Musick et al. (1983) greatly reduced deep percolation losses by using tractor traffic and wide furrow spacings (alternate furrows) on a permeable soil, and the practices did not reduce corn yields. Surface irrigation technology can be efficient on a farm or field basis when runoff water is captured and reused, and when managed to avoid or minimize percolation losses. Surface irrigation often is termed "low tech" because it mainly involves manual labor for water control, but it can involve many "high tech" (e.g., automated controls on canals and pipelines using radio, satellite, or cellular telephone communications) components.

Advanced surface irrigation technologies can range from moderately "high tech" [e.g., automated surge flow using micro-computer controlled valves to reduce field runoff while achieving a more even irrigation (Bishop et al., 1981; Kemper et al., 1988)] to precise laser-leveling of irrigated basins (Dedrick et al., 1982). Other automated devices for improving surface irrigation range from simple valves to cablegation (Kemper et al., 1981, 1985; Kruse et al., 1990). Also, as previously mentioned, treating water with PAM can enhance infiltration and reduce erosion. Achieving a high surface irrigation efficiency level requires keen management and knowledge of irrigation

hydraulics, on-site soil processes (e.g., infiltration), and soil variability, regardless of system sophistication.

The main limitations and challenges for surface irrigation remain avoiding excessive deep percolation and reducing and/or eliminating runoff. Stewart et al. (1983) developed the LID (limited irrigation-dryland) furrow-irrigation system that involved limited surface applications to avoid deep percolation at the input end while not irrigating the lower end where furrow dikes were installed to impound water from rain. The system is applicable for use in continental-climate regions where some growing season rain occurs, but where the irrigation water supply is limited (e.g., many semiarid regions). Improved water use efficiency resulted from making better use of rainfall and maximizing the benefit from irrigation.

Canal linings (cement or flexible membranes) and underground pipelines [cement or polyvinyl chloride (PVC)] are highly effective for reducing irrigation water transport losses. Use of gated pipes (aluminum, PVC, or flexible materials) can reduce surface ditch seepage and spillage losses. Also, tailwater (irrigation runoff) reuse can reduce net irrigation water losses. Because most surface irrigation involves low pressures, energy required for pumping water is low, except when the source is a deep well.

Sprinkler irrigation technology can be quite varied also (Keller and Bliesner, 1990). Goals for sprinkler irrigation are to "remove" soil from its conveyance role by using pressurized pipelines and to use the kinetic force of the pressurized water to distribute the water in droplet form (like rain) directly to the crop and/or soil. System pressure and nozzle diameter affect droplet diameter and, hence, the kinetic energy that drops impart at the soil surface. Large droplets can break down surface soil aggregates, cause surface sealing, and impede water infiltration. Small drops can evaporate more quickly and drift from the target, thus reducing the amount of water reaching the crop.

Solid set and mechanical types (e.g., center pivots) can be automatically and/or remotely controlled without much difficulty. Use of sprinklers should eliminate or allow better control of deep percolation losses and practically eliminate runoff from irrigation, but uneven water distribution due to system hydraulics or wind effects on spray patterns are possible. Using lower angle and closer sprinkler or spray head spacings can reduce wind effects on water distribution.

Center pivots can be equipped with spray heads that cover a smaller wetted diameter, are closer to the ground or crop to reduce wind effects and evaporation, and operate at lower pressures (Gilley and Mielke, 1980). Use of these devices, however, can result in instantaneous water application rates that exceed the soil's infiltration rate and, therefore, surface water redistribution and/or runoff. For example, Clothier and Green (1994) reported extreme macropore flow and nonuniform soil wetting when the application rate was

102 mm hour⁻¹ as compared to that when the rate was 4 mm hour⁻¹. Lyle and Bordovsky (1981, 1983) developed LEPA (low energy precision application) technology for center pivots and lateral-move machines to eliminate evaporative losses, surface redistribution, and runoff. LEPA irrigation is intended for use in conjunction with furrow dikes that impound irrigation and rain water. Users of LEPA system usually apply water to alternate furrows through furrow bubbles or drag socks (Fangmeier et al., 1990). Grain crop yields differed little when adequate water was applied using LEPA and spray irrigation at Bushland, which is at a semiarid site (Schneider and Howell, 1990, 1999). Schneider (1999) reviewed much of the literature on LEPA and spray irrigations and concluded, based on efficiency and uniformity, that neither method "could be considered inherently superior to the other." However, when irrigation capacity (flow rate per unit area) becomes low and deficit irrigation is intentionally practiced, as for cotton in the U.S. Southern High Plains, then LEPA irrigation would be preferable.

Drip and trickle irrigation, now widely called microirrigation (MI) (Camp, 1998; Kruse et al., 1990), was developed mainly in Israel and is now used worldwide. MI is used on over half of Israel's irrigated land and on over 400,000 ha in California (Gleick, 1998). With MI, objectives are to "remove" soil and air as distribution mediums, as occurs with surface and sprinkler irrigation, and to irrigate only the minimum root zone volume needed for each plant. A range of technologies encompass both surface and subsurface MI, and many types of applicators are available [drippers, line-source pipes, bubblers, small spray heads, and even small sprinklers (or rotators)].

Subsurface MI systems, called SDI (subsurface drip irrigation), are installed at soil depths ranging from a few centimeters (may be placed on the surface, then covered with cultivators) to, for example, at 30 cm (installed with special chisel shanks). Deeper placements make seed germination difficult, and water from rain or portable sprinklers may be needed for crop establishment. Lateral line spacing for SDI systems can vary, depending on the crop grown and its culture. For field crops, one line often is placed midway between two rows to reduce the cost.

The main intent of using MI is to apply the precise amount of water needed by each plant at exactly the time when it needs it (Nakayama and Bucks, 1986). MI may not result in wetting the whole soil surface as with most surface irrigation and sprinkler systems, but the area (or root volume) is irrigated more frequently. Typically, MI may involve irrigation intervals of one or a few days, but can involve multiple "pulses" in a single day.

MI involves a massive pipe network compared to that with surface or sprinkler irrigation, but the pipes usually are small because of low flow rates. Also, material (polyethylene, PE, PVC, etc.) costs are lower because a lower

pressure (70 to 140 kPa) can be used. Because MI involves an extensive pipe network, it was first successfully used in orchards and vineyards with low plant densities (Abbott, 1984). Now, MI is used for many row crops, but more often for high-value vegetable crops. For higher-valued vegetables in rows, it often is used under a plastic mulch. SDI is now commonly used for row crops (e.g., cotton and corn) and for vegetables. MI systems are easily automated and controlled with devices such as simple timers and microcomputers, and they easily can be used to apply nutrients to crops.

Runoff should not occur with MI because water applications are small (ranging from 2-20 mm, but typically 5-10 mm). Deep percolation can be controlled more easily with the small applications. Also, there is less dependence on water storage in the root zone because water can be applied more frequently than where larger amounts are required to achieve uniform coverage with surface irrigation methods. Use of SDI can even reduce evaporation because the soil surface usually is not wetted. In practice, with many SDI systems, except those installed deeper than 30 cm, some surface wetting occurs due to capillary water flow and total elimination of soil water evaporation should not be expected. Also, significant evaporative losses may occur because the area is irrigated more frequently. Many times, however, the wetted area is beneath the crop canopy and evaporation might still be low.

Use of MI requires water filtration and/or chemical treatment to avoid plugging the small passageways by sand or other inorganic materials, bicarbonate (lime) and iron (ochre) deposits, and slime-forming organisms. Plugging can result in poor performance (low uniformity) or complete failures of systems in some cases. Although many water filtration and water treatment functions can be automated, careful operator attention is required.

Irrigation Management for Conserving Water

As defined previously, irrigation management encompasses more than just decisions on when and how much to irrigate. Operation and maintenance are critical elements, but they depend on the specific irrigation hardware being used. Maintenance may range from installing and maintaining a surface ditch to maintaining the intricate mechanism of the tower drive for a center pivot sprinkler. Daily maintenance may be needed in some cases; possibly only annual checking in others. Proper equipment maintenance can avoid breakdowns at critical times when a missed irrigation would be highly detrimental for a crop.

Irrigation management is broadly related to irrigation scheduling. Although simple in concept (when to irrigate and how much water to apply), it is complex for the "whole" farm decision making process that involves strategic (before the season) and tactical (on the spot day-to-day) planning. The goal is to decide how to achieve the greatest net return from the fixed and

variable costs and the value of the crop produced, subject to all constraints (land, labor, water, environment, salinity, legal, etc.). Thus, irrigation water management and its conservation may not always go hand in hand.

When to use a preplant irrigation is one strategic decision that can greatly affect subsequent decisions about irrigating. A preplant irrigation may be used for weed seed germination, profile water replenishment, leaching, seed bed preparation, etc. Whereas significant profile replenishment with water is difficult with MI and most sprinkler systems, excessive infiltration rates can sometimes lead to large percolation losses for the first surface-applied irrigation after primary tillage. Generally, when rainfall before planting is near or above normal, preplant irrigations do not increase crop yields (Musick and Lamm, 1990). In some cases, early spring soil water loss rates and low rainfall may dictate that a preplant irrigation be made for a summer crop (Musick et al., 1971). When needed, it should be carefully planned and executed to minimize deep percolation (unless leaching is desired) and applied shortly before planting.

Irrigation scheduling can involve using a wide range of tools, depending on several circumstances, including the irrigation method used. For each method, an "optimum" application range may be most appropriate. With surface irrigation methods, water typically is applied more efficiently and evenly when the amounts range from 70 to 120 mm, depending on the soil type, surface slope, and field geometry (length of run, furrow spacing, border width, etc.). Traditional sprinkler methods may be more suited for applications of ~ 10 to 50 mm. For MI, amounts ranging from 5 to 25 mm might be better, depending on the soil. These "optimum application ranges" will be site and system specific, but a few field trials and routine evaluations (Merriam and Keller, 1978) can be used to identify the operational parameters needed for achieving the desired level of irrigation uniformity and efficiency.

The desired irrigation frequency (F , days) is a direct function of application depth and irrigation capacity (flow rate per unit area), and can be computed as

$$F = D_o / (Q \times 86,400) \quad [1]$$

where D_o is optimum application depth (mm), Q is irrigation capacity ($L s^{-1} m^{-2}$), and 86,400 (a constant) is seconds in a day. Irrigation capacity is determined by the supply rate and the area being irrigated. It is closely aligned with a crop's "peak" irrigation requirement rate (usually expressed in $mm d^{-1}$). This rate is largely determined by the "peak" ET rate, and is influenced by crop type, the environment, "effective" rainfall, soil type (water holding capacity and depletion permissible without reducing crop yield potential), and irrigation system efficiency.

The peak requirement rate is an irrigation system design parameter that

influences many aspects of irrigation, including scheduling. It affects system fixed costs because it determines the pipe sizes needed for that flow rate and variable costs because it affects pumping costs that are a function of the flow rate. Therefore, it is desirable to keep the irrigation capacity (Q) as small as practical and at an acceptable level of risk of not being able to meet the desired crop ET rate, but as large as possible to provide the greatest flexibility in irrigation scheduling.

Irrigation timing affects water conservation in two important ways (Martin et al., 1990). One pertains to the earliest date to irrigate without having appreciable water losses (typically runoff and deep percolation); it depends largely on the irrigation system and the soil's water content and water holding capacity. The second pertains to the date for the last irrigation without inflicting a significant water deficit and "potential" yield loss on the crop. It depends on the soil, crop grown, crop growth stage, and expected ET rate. In this case, the soil profile likely will not be filled to capacity, thus providing an opportunity for water storage from rain. The scheduling decisions will be subject to weather forecasts (rain and other parameters that affect ET rates).

Irrigation timing decisions can be based on simple calendars (based on "normal" ET and precipitation) (Hill and Allen, 1996), checkbook type approaches (summations of water additions and consumptive use), tracking crop water use with computer models (based on crop ET or growth), or direct sampling of the soil or crop water status. The decision should incorporate the crop's growth stage and its sensitivity to water deficits at that particular stage. Phene et al. (1990) reviewed many techniques for sensing a crop's need for irrigation. Besides determining when to irrigate, field sampling (soil or crop water status sensing) is critical for evaluating system performance (spotting areas of poor coverage or where system errors and/or malfunctions may have occurred).

Remote sensing (aerial photography or satellite imagery) is an additional useful irrigation management tool. Good crop or soil sensing along with remote sensing can guide irrigation scheduling models as well. As such, ET modeling and sensing (remote and ground based) should be regarded as complementary rather than individual or mutually exclusive tools for irrigation scheduling.

Conserving water through irrigation management largely rests on the irrigation supply capacity (irrigation capacity and/or any legal water use constraints), crop response (yield and/or quality) to irrigation water, and irrigation economics (fixed and variable irrigation costs) (English et al., 1990). Certainly, excessive irrigations that do not contribute to meeting crop water requirements (including leaching to control salinity) should be eliminated (Clothier, 1989). Increasing an irrigation system's efficiency and enhancing its uniformity should be considered next. All irrigations involve

some nonuniformity (some areas receive more water while others receive less than the mean). Small under irrigations (5-10%) may be undetectable in most cases and have not affected crop yields in most studies (in some, crop quality concerns occurred).

Water for irrigation is limited in many parts of the world (Gleick, 1998). Adequate water for fully meeting crop needs is available on few farms in the western part of the U.S. Southern High Plains (Musick et al., 1987). In India, the National Water Commission based irrigation planning on a "50% dependable" water supply (Chitale, 1987). Use of deficit irrigation can be effective for soils with plant available water contents exceeding 125 mm (Keller and Bliesner, 1990) and often results in crop yields less than the maximum attainable, but reduces irrigation water use, enhances crop water use efficiency, and improves the capture and use of rainfall. However, soil salinity levels must be monitored and appropriate leaching and reclamation measures must be implemented to protect the soil from salinization in many cases.

CONCLUSIONS

All plants depend on an adequate water for optimum growth and yield. Globally, adequate water usually is available in humid regions, but limited precipitation in subhumid and semiarid regions often limits the supply for nonirrigated crop production. When available, water from streams, reservoirs, or aquifers often is used for irrigation in subhumid and semiarid regions, and to extend crop production into arid regions. Sometimes, crops are irrigated in humid regions. Our emphasis, however, was on water conservation for dryland crops in subhumid and semiarid regions and irrigated crops in subhumid to arid regions.

The total amount of water globally available annually for all purposes is relatively constant, but highly variable temporally and spatially, especially in subhumid, semiarid, and arid regions. Also, urban, industrial, environmental, and recreational users increasingly are competing with agriculture for available supplies. The ever-increasing world population, however, requires an ever-increasing supply of food and fiber. To meet this demand, agriculture must produce more with less water, and agriculture must do its share to conserve water so that adequate water will be available for all users.

Crop production requires a large amount of water. Much water potentially available for crop use, however, is not conserved, and water initially conserved often is not used efficiently. Under all conditions, agricultural water conservation depends on water infiltration into soil and its retention for later extraction by plant roots. Water conservation on dryland and with irrigation often involves reducing water losses due to runoff, evaporation, deep per-

colation, and use by weeds, and increasing water retention in the soil profile. Under some conditions, however, runoff may be captured down slope for immediate use by crops, stored in reservoirs for later irrigation, or enter streams and used for other purposes, including irrigation. Also, water percolation to depths beyond the root zone is allowed to control salinity in some soils.

The principles of agricultural water conservation are discussed, and they are applicable regardless of tract and equipment size or technology level involved. Although most practices involving the principles are suitable for dryland and irrigated conditions, the size and technology level constraints sometimes limit the adaptability of some practices to achieve the conservation goals. In addition, water conservation for irrigated agriculture is influenced by the water delivery system, irrigation method, and level of technology used, and by management decisions. With good management and adoption of appropriate practices, improved agricultural water conservation and subsequent use of that water for greater crop production are possible under dryland and irrigated conditions, thus helping to meet the water needs of all users and providing for the food and fiber needs of the increasing global population.

REFERENCES

- Abdullah, S.M., R. Horton, and D. Kirkham. (1985). Soil water evaporation suppression by sand mulches. *Soil Science* 139: 357-361.
- Abbot, J.S. (1984). Micro irrigation—World wide usage. *ICID Bulletin* 33: 4-9.
- Abu-Awwad, A.M. and M.R. Shatanawi. (1997). Water harvesting and infiltration in arid areas affected by surface crust: Examples from Jordan. *Journal of Arid Environments* 37: 443-452.
- Agassi, M., I. Shainberg, D. Warrington, and M. Ben-Hur. (1989). Runoff and erosion control in potato fields. *Soil Science* 148: 149-154.
- Alegre, J.C. and M.R. Rao. (1996). Soil and water conservation by contour hedging in the humid tropics of Peru. *Agriculture, Ecosystems & Environment* 57: 17-25.
- Amir, J. and T.R. Sinclair. (1996). A straw mulch system to allow continuous wheat production in an arid climate. *Field Crops Research* 47: 21-31.
- Beach, T. and N.P. Dunning. (1995). Ancient Maya terracing and modern conservation in the Petén rain forest of Guatemala. *Journal of Soil and Water Conservation* 50: 138-145.
- Benyamini, Y. and P.W. Unger. (1984). Crust development under simulated rainfall on four soils. *Agronomy Abstracts*, pp. 243-244.
- Bertrand, A.R. (1966). Water conservation through improved practices. In *Plant Environment and Efficient Water Use*, eds. W.H. Pierre, D. Kirkham, and R. Shaw. Madison, WI: American Society of Agronomy, pp. 207-235.
- Bishop, A.A., W.R. Walker, N.L. Allen, and G.J. Poole. (1981). Furrow advance rates under surge flow systems. *Journal of Irrigation and Drainage Division (ASCE)* 107(IR3): 257-264.

- Black, A.L. (1986). Resources and problems in the northern Great Plains area. In *Planning and Management of Water Conservation Systems in the Great Plains States, Proceedings of a Workshop*, Lincoln, NE, October 1985. Lincoln, NE: U.S. Department of Agriculture, Soil Conservation Service, Midwest National Technical Center, pp. 25-38.
- Black, A.L. and J.K. Aase. (1988). The use of perennial herbaceous barriers for water conservation and the protection of soils and crops. *Agriculture, Ecosystems and Environment* 22/23: 135-148.
- Black, A.L. and A. Bauer. (1986). Soil water conservation strategies for Northern Great Plains. In *Planning and Management of Water Conservation Systems in the Great Plains States, Proceedings of a Workshop*, Lincoln, NE, October 1985. Lincoln, NE: U.S. Department of Agriculture, Soil Conservation Service, Midwest National Technical Center, pp. 76-86.
- Black, A.L. and F.H. Siddoway. (1976). Dryland cropping sequences within a tall wheatgrass barrier system. *Journal of Soil and Water Conservation* 31: 101-105.
- Black, A.L. and D.L. Tanaka. (1996). A conservation tillage-cropping systems study in the northern Great Plains of the USA. In *Soil Organic Matter in Temperate Agroecosystems*, eds. E.A. Paul, K.A. Paustian, E.T. Elliott, and C.V. Cole. Boca Raton, FL: Lewis Publishers, pp. 335-342.
- Brady, N.C. (1988). Scientific and technical challenges in dryland agriculture. In *Challenges in Dryland Agriculture—A Global Perspective*, eds. P.W. Unger, T.V. Sneed, W.R. Jordan, and R. Jensen. College Station, TX: Texas Agricultural Experiment Station, pp. 6-12.
- Brown, P.L., A.D. Halvorson, F.H. Siddoway, H.F. Mayland, and M.R. Miller. (1982). Saline-seep diagnosis, control, and reclamation. *U.S. Department of Agriculture Conservation Research Report No. 30*. Washington, DC: U.S. Government Printing Office.
- Burt, C.M., A.J. Clemmens, T.S. Strelkoff, K.H. Solomon, R.D. Bliesner, L.A. Hardy, T.A. Howell, and D.E. Eisenhauer (1997). Irrigation performance measures: Efficiency and uniformity. *Journal of Irrigation and Drainage Engineering* 123: 423-442.
- Camp, C.R. (1998). Subsurface drip irrigation: A review. *Transactions of the ASAE* 41: 1353-1367.
- Campbell, C.A., B.G. McConkey, V.O. Biederbeck, R.P. Zentner, D. Curtin, and M.R. Peru. (1998). Long-term effects of tillage and fallow-frequency on soil quality attributes in a clay soil in semiarid southwestern Saskatchewan. *Soil & Tillage Research* 46: 135-144.
- Campbell, C.A., B.G. McConkey, R.P. Zentner, F. Selles, and F.B. Dyck. (1992). Benefits of wheat stubble strips for conserving snow in southwestern Saskatchewan. *Journal of Soil and Water Conservation* 47: 112-115.
- Cannell, G.H. and H. E. Dregne. (1983). Regional setting. In *Dryland Agriculture, Monograph 23*, eds. H.E. Dregne and W.O. Willis. Madison, WI: American Society of Agronomy, Inc., Crop Science Society of America, Inc., and Soil Science Society of America, Inc., pp. 3-17.
- Carroll, C., H. Halpin, P. Burger, K. Bell, M.M. Sallaway, and D.F. Yule. (1997). The

- effect of crop type, crop rotation, and tillage practice on runoff and soil loss on a Vertisol in central Queensland. *Australian Journal of Soil Research* 35: 925-938.
- Chitale, M.A. (1987). Water management in drought prone areas. *Water Supply* 5:11-130. Oxford.
- Choudhary, M.I., A.A. Shalaby, and A.M. Al-Omran. (1995). Water holding capacity and evaporation of calcareous soils as affected by four synthetic polymers. *Communications in Soil Science and Plant Analysis* 26(13&14): 2205-2215.
- Clothier, B.E. (1989). Research imperatives for irrigation science. *Journal of Irrigation and Drainage Engineering (ASCE)* 115: 421-448.
- Clothier, B.E. and S.R. Green. (1994). Rootzone processes and the efficient use of irrigation water. *Agricultural Water Management* 25: 1-12.
- Cogle, A.L., M. Littleboy, K.P.C. Rao, G.D. Smith, and D.F. Yule. (1996). Soil management and production of Alfisols in the semi-arid tropics: III. Long-term effects on water conservation and production. *Australian Journal of Soil Research* 34: 103-111.
- Critchley, W.R.S., C. Reij, and T.J. Willcocks. (1994). Indigenous soil and water conservation: A review of the state of knowledge and prospects for building on traditions. *Land Degradation & Rehabilitation* 5: 293-314.
- Cutforth, H.W. and B.G. McConkey. (1997). Stubble height effects on microclimate, yield and water use efficiency of spring wheat grown in a semiarid climate on the Canadian prairies. *Canadian Journal of Plant Science* 77: 359-366.
- de Jong, E. and H. Steppuhn. (1983). Water conservation: Canadian Prairies, In *Dryland Agriculture*, ed. H.E. Dregne and W.O. Willis. Madison, WI: American Society of Agronomy, Inc., Crop Science Society of America, Inc., and Soil Science Society of America, Inc., pp. 89-104.
- Dedrick, A.R., L.J. Erie, and A.J. Clemmens. (1982). Level-basin irrigation. In *Advances in Irrigation*, Volume 1. ed. D. Hillel. New York, NY: Academic Press, Inc., pp. 105-145.
- Eck, H.V. and H.M. Taylor. (1969). Profile modification of a slowly permeable soil. *Soil Science Society of America Proceedings* 33: 779-783.
- English, M.J., J.T. Musick, and V.V.N. Murty. (1990). Deficit irrigation. In *Management of Farm Irrigation Systems*, eds. G.J. Hoffman, T.A. Howell, and K.H. Solomon. St. Joseph, MI: American Society of Agricultural Engineers, pp. 631-663.
- Fangmeier, D.D., W.F. Voltman, and S. Eftekharzadeh. (1990). Uniformity of LEPA irrigation systems with furrow drops. *Transactions of the ASAE* 33: 1907-1912.
- FAO (Food and Agriculture Organization of the United Nations, Rome, Italy). (1998). World irrigated area. *The FAOSTAT Database*, FAOSTAT Agricultural Data. <http://apps.fao.org/lim500/nph-wrap.pl?Irrigation&Domain=LUI&servlet=1>
- Frasier, G.W. and L.E. Myers. (1983). *Handbook of Water Harvesting*, Agriculture Handbook 600. Washington, DC: U.S. Department of Agriculture, Agricultural Research Service.
- Gallacher, R.N. (1990). The search for low-input soil and water conservation techniques. In *Topics in Applied Resource Management*, Volume 2, *Experiences with Available Conservation Technologies*, eds. E. Baum, P. Wolff, and M.A. Zöbisch. Wittenhausen, Federal Republic of Germany: German Institute for Tropical and Subtropical Agriculture, pp. 11-37.

- Gilley, J.R. and L.N. Mielke. (1980). Conserving energy with low-pressure center pivots. *Journal of Irrigation and Drainage Division (ASCE)* 106(IR1): 49-59.
- Gilley, J.E., S.C. Finkner, R.G. Spomer, and L.N. Mielke. (1986). Runoff and erosion as affected by corn residues: Part I. Total losses. *Transactions of the ASAE* 29: 157-160.
- Gleick, P.H. (1998). *The world's water, 1998-1999*. Washington, DC: Island Press.
- Good, L.G. and D.E. Smika (1978). Chemical fallow for soil and water conservation in the Great Plains. *Journal of Soil and Water Conservation* 33: 89-90.
- Greb, B.W. (1983). Water conservation: Central Great Plains, In *Dryland Agriculture*, ed. H.E. Dregne and W.O. Willis. Madison, WI: American Society of Agronomy, Inc., Crop Science Society of America, Inc., and Soil Science Society of America, Inc., pp. 57-72.
- Greb, B.W. (1979). Reducing drought effects on croplands in the west-central Great Plains. *U.S. Department of Agriculture Bulletin No. 420*. Washington, DC: U.S. Government Printing Office, 31 pp.
- Harper, J. and O.H. Brensing. (1950). Deep plowing to improve sandy land. *Bulletin B-362*. Stillwater, OK: Oklahoma Agricultural Experiment Station.
- Harrold, L.L. and W.M. Edwards. (1972). A severe test of no-till corn. *Journal of Soil and Water Conservation* 27: 30.
- Hien, F.G., M. Rietkerk, and L. Stroosnijder. (1997). Soil variability and effectiveness of soil and water conservation in the Sahel. *Arid Soil Research and Rehabilitation* 11: 1-8.
- Hill, R.W. and R.G. Allen. (1996). Simple irrigation scheduling calendars. *Journal of Irrigation and Drainage Engineering (ASCE)* 122: 107-111.
- Hoffman, G.J., T.A. Howell, and K.H. Solomon (eds.). (1990). *Management of Farm Irrigation Systems*. St. Joseph, MI: American Society of Agricultural Engineers, 1040 p.
- Howell, T.A., A. Yazar, A.D. Schneider, D.A. Dusek, and K.S. Copeland. (1995). Yield and water use efficiency of corn in response to LEPA irrigation. *Transactions of the ASAE* 38: 1737-1747.
- Jacks, G.V., W.D. Brind, and R. Smith. (1955). Mulching. *Commonwealth Bureaux of Soil Science (England) Technical Communication* 49. Farnham Royal, Bucks., England: Commonwealth Agricultural Bureaux.
- Jalota, S.K. (1993). Evaporation through a soil mulch in relation to mulch characteristics and evaporativity. *Australian Journal of Soil Research* 31: 131-136.
- Jalota, S.K. and S.S. Prihar. (1990). Bare-soil evaporation in relation to tillage. *Advances in Soil Science* 12: 187-216.
- Johnson, W.C. (1964). Some observations on the contribution of an inch of seeding time soil moisture to wheat yields in the Great Plains. *Agronomy Journal* 56: 29-35.
- Jones, O.R. (1981). Land forming effects on dryland sorghum production in the southern Great Plains. *Soil Science Society of America Journal* 45: 606-611.
- Jones, O.R. and R.N. Clark. (1987). Effects of furrow dikes on water conservation and dryland crop yields. *Soil Science Society of America Journal* 51: 1307-1314.